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MACKINAC STRAITS BRIDGE

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STRUCTURAL DIVISION

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THIS PAPER

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MACKINAC STRAITS BRIDGE

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SYNOPSIS

The bridging of Mackinac Straits in Michigan has captured the imagination of engineers for the past half-century. Recent rapid growth in traffic now demands the realization of this project. The need for the bridge is set forth in terms of the industrial potential of the Great Lakes Area, the growth of automobile and truck traffic, and the estimated annual revenue to be derived from tolls.

Development of the project over the last thirty years is outlined, and the location and geology of the site are described. The span layout of the bridge is detailed, together with roadway widths, grades and clearances.

Of primary interest, the proportions of the 3800-ft. span suspension bridge are described. The applied principles of design for aerodynamic stability are presented and are illustrated by reference to the design features of the structure together with the very favorable results of wind tunnel tests on section models of the span. The governing features of the design of the suspension bridge foundations are outlined.

In conclusion the cost of the project is summarized and its economic justification and financial feasibility are discussed.

Need for Mackinac Straits Bridge

The four-mile wide Straits of Mackinac join Lake Michigan and Lake Huron, Fig. 1, and, together with the Lakes, divide the State of Michigan into the 41,678 square-mile Lower Peninsula and the 16,538 square-mile Upper Peninsula.

The Mackinac Straits Bridge will replace the existing State-operated highway ferry system in order to provide an all-year, all-weather direct connection between these two great Peninsulas of Michigan.

Despite the fact that the far greater part of the population of the State is concentrated in the highly industrialized Lower Peninsula and its large cities such as Detroit, the Upper Peninsula is possessed of immense natural resources, which when further developed, will attract additional population and industrial activity. At present the principal industries of the Upper Peninsula are as follows in the order of their importance: forestry and forest products, mining, recreation, and agriculture.

The Upper Peninsula is equivalent in area to Massachusetts, Rhode Island, Connecticut and part of New Hampshire; and 87 per cent of this area is forested in commercial timber. Copper and Iron ore reserves are concentrated in the western sections of the Upper Peninsula. Indeed, this part of Michigan, well-known as "The Copper Country," is now enjoying a resurgence of activity with the establishment of the White Pine Copper Mine development and the reactivation of the Osceola Copper Mine, in addition to the rich mining activity

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Fig. 1. Location Map of Mackinac Straits, Michigan.

which has continued for years in that area of the country.

It is recognized that the project which would contribute most to the betterment and further development of the Upper Peninsula is the Mackinac Straits Bridge. But, in a larger measure, it will contribute to the betterment of Michigan as a whole and of the entire Great Lakes area as well as of the Province of Ontario in Canada. Within a radius of 500 miles from the Straits of

Mackinac there resides a population of 30,000,000 people in the United States and Canada who will benefit from the construction of the Mackinac Straits Bridge, and who in turn insure the economic feasibility of the Project.

The major highways of Michigan converge at or near Mackinaw City on the south and at St. Ignace on the north of the Straits of Mackinac. Thus, the Mackinac Straits Bridge will funnel traffic from the Lower Peninsula into the Upper Peninsula and then into Canada by way of Sault Ste. Marie, 50 miles north of the Straits. Furthermore, the Straits Crossing will provide a shorter east-west route for bonded truck traffic between the western provinces of Canada and populous southeastern Ontario. With this strategic location, the Mackinac Straits Bridge will be an outstanding connecting link in the nation's highway system, of high strategic importance in our Continent's defense program.

Truck traffic on the Mackinac Straits ferries has been increasing rapidly since 1950 when a strike on the Canadian Railways forced shippers to go to trucking. Truckers hauling between the western provinces of Canada and southeastern Ontario can shorten delivery time by as much as two to four days compared to shipments on the Canadian railroads. The estimated truck traffic for 1953 is 97,200 in a total estimated ferry traffic of 809,000 vehicles, and it is expected to increase at a rapid rate.

The Mackinac Ferry rates were increased about 50% June 1, 1953 for the first time since the 1930's, and in spite of this increase in rates, traffic has increased 12% over the same period of 1952. Coverdale and Colpitts, traffic consultants to the Mackinac Straits Bridge Authority, estimate that the ferry traffic will be over one million vehicles by 1957, and that with completion of the bridge by that time, the bridge-induced increase in traffic would amount to at least 75%, producing a total estimated bridge traffic of 1,927,000 vehicles in 1957. The 75% estimate of bridge induced traffic is considered conservative in the light of the waiting-in-line time at the ferry observed this past summer which was from three to 4-1/2 hours. At times over 1,000 cars were waiting in the parking lot for ferry service, Fig. 2, Fig. 3. At an average toll rate of $3.08, with $2.10 for passenger autos, the estimated gross revenue for 1957 is $5,935,000.

The Design of the Mackinac Straits Bridge

The designs for great engineering works, with some exceptions, are not born full-grown; they are the end result of the past endeavors of the engineering profession and the construction industry. If engineering is to progress, it is imperative that each new project should express some development in the science and art of engineering. But in the main, the design of each new project will depend on the tried practice of the past and the tested experience of other engineers.

This is true of the Mackinac Straits Bridge.

History of the Project

For the past half-century the bridging of the Straits of Mackinac has been a challenge to engineers and to the people of Michigan. Transportation between the Upper and Lower Peninsulas of Michigan has been maintained by railroad ferry since 1881 and by vehicular ferries since 1923. The demand for a vehicular crossing by bridge or tunnel has resulted in a series of studies of such a project since 1920 when the late Horatio S. Earle, Highway Commissioner, suggested a submerged tunnel for the site. In 1928 the Highway

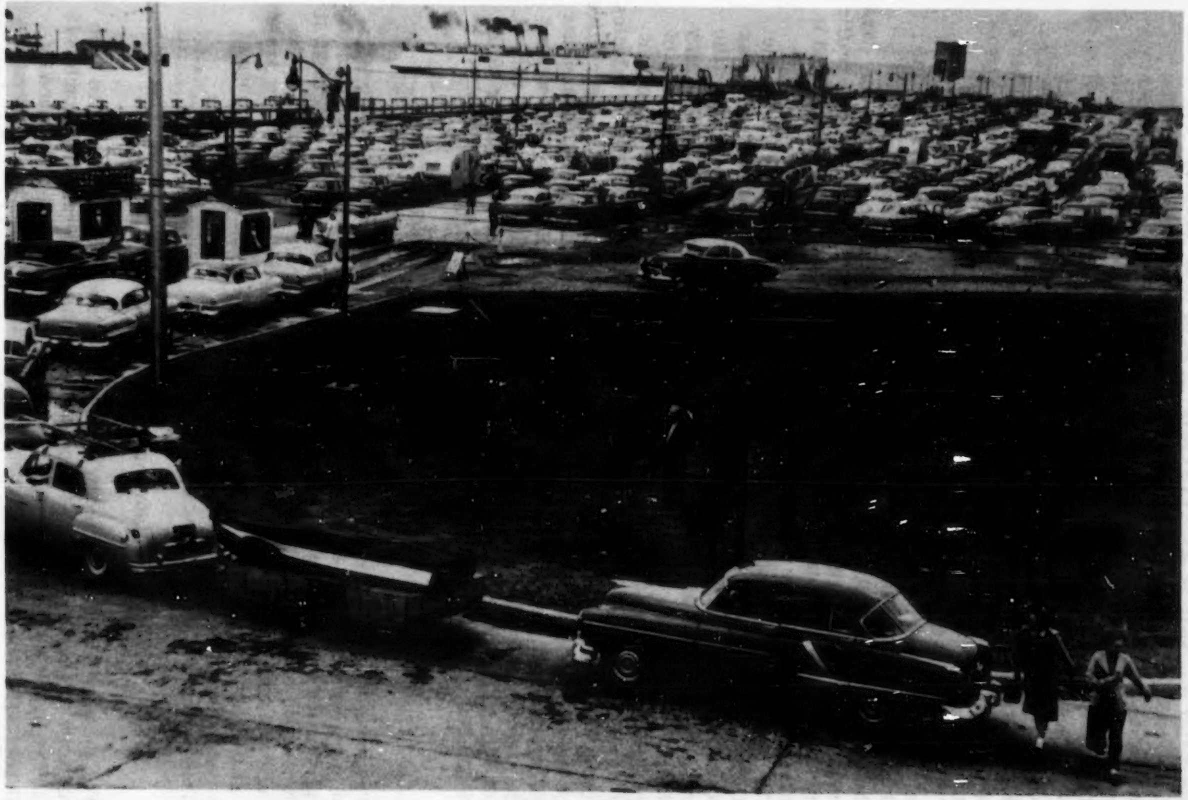

Fig. 2. Cars Waiting for Ferry Crossing - Mackinaw City Dock. (South Side of Strait.)

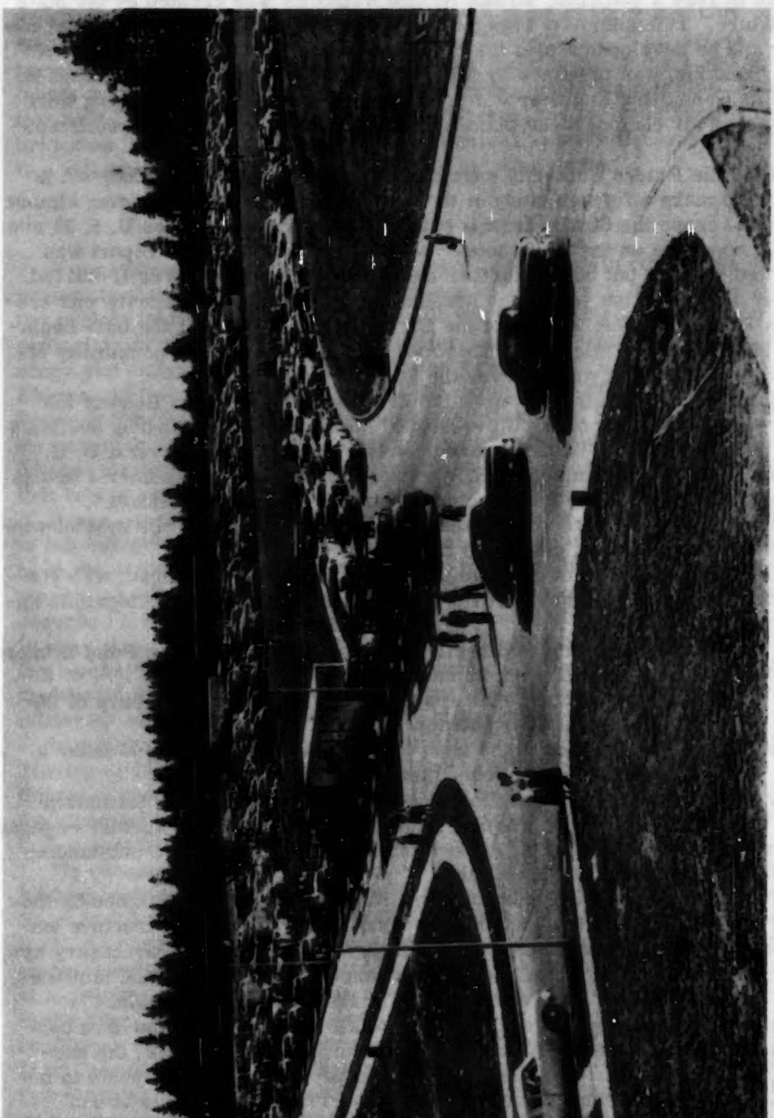

Fig. 3. Cars Waiting for Ferry Crossing - St. Ignace Dock.
(North Side of Strait.)

Department concluded that a bridge between Mackinaw City and St. Ignace would be feasible, but the project was not developed.

Then in 1934 a Mackinac Straits Bridge Authority was created by the State Legislature. This authority engaged Mr. C. E. Fowler as temporary chief engineer and he developed a plan for the crossing. In 1935 another plan for a direct crossing, was prepared by Mr. Francis C. McMath, with Mr. James H. Cissel as Consulting Engineer.[2] Applications to the PWA for financing were disapproved for each of these plans and the project was again dropped temporarily.

In 1938 the Bridge Authority engaged the engineering firm of Modjeski & Masters to make a further study of the project and a bridge "extending almost due north across the Straits from a point at which highway routes U. S. 31 and U. S. 23 converge on the south shore" was recommended. This report was submitted in 1940, but before further steps were taken World War II started.

After a lapse of ten years, the present Mackinac Bridge Authority was created by P. A. 21 of Public Acts of the Extra Session of 1950 of the 65th Legislature of the State of Michigan. This Authority now has the responsibility of the construction of a crossing over the Straits.

In July 1950, this Authority, upon the recommendation of the Dean of the College of Engineering of the University of Michigan, as provided by Section 4 of the Bill, appointed a Board of three consulting engineers, Messrs. O. H. Ammann, D. B. Steinman and G. B. Woodruff, to "Determine whether a bridge can be safely and feasibly constructed across the Straits of Mackinac".

This Board, in their report of January 10, 1951, confirming the previous investigations and reports, concluded that:

"(1) The construction of a bridge across the Straits of Mackinac, with construction methods which have proven successful on other large bridges, is entirely feasible.

(2) The location of a bridge directly northward from Mackinac Point is more suitable than other locations which had previously been proposed.

(3) The bridge can be completed ready for traffic within four years of the award of the first construction contract."

The Authority also engaged the firm of Coverdale and Colpitts to make a traffic analysis and assist in an economic study.

In view of the important question of the suitability of the rock formation under the Straits to carry the bridge foundations, the Authority further engaged the services of Dr. Charles P. Berkey and Dr. Sidney Paige, two outstanding engineering geologists, as consultants.

In January 1953, D. B. Steinman, Consulting Engineer, was retained by the Authority to design and to supervise the construction of the substructure and superstructure of a bridge across the Straits, together with the necessary approaches, Administration Building, Maintenance and Toll Collection facilities. Mr. Glenn B. Woodruff was engaged by D. B. Steinman as consultant.

Due credit must be given to the efforts of all the engineers who have contributed to the development of this project. But in a larger sense, the successes and the failures of the past as in other projects, are guideposts to the designers of the Mackinac Straits Bridge. The Trans-Bay Bridge in San Francisco with its 242-ft. deep foundation, the Golden Gate Bridge with the 4,200-ft. longest span, the original and the new Tacoma Bridge with its lessons in aerodynamic design, supplemented by wide aerodynamic research, all have led the way to the design of this bridge.

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2. The Proposed Mackinac Straits Bridge - James H. Cissel, Civil Engineering, October, 1937.

Location

The selected bridge location, Fig. 4, extends almost due north across the Straits to St. Ignace and U. S. Route 2 from a point in Mackinaw City on the South where U. S. Route 31 and U. S. Route 23 converge. This location was determined by a previous study, and in 1940 a mole or fill some 3,500 ft. in length was constructed into the Straits from St. Ignace on this line. The location best fits the existing State Highway System, and the construction of the bridge on this location will be most economical because the length of crossing is a minimum and full use is made of the existing mole.

Geology

A question which has given rise to much discussion in connection with this project is the geology at the site. Because of its unusual brecciated formation, the geology of the area has, for over 100 years, attracted the attention of the geologist. With the growing necessity for a bridge across the Straits, the geology was exhaustively studied by Professors Kenneth K. Landes, George M. Ehlers and George M. Stanley, under the direction of State Geologist R. A. Smith.[3] Two features are pertinent to the planning of the bridge—the breccia formation and the hidden rock gorge. A further geological report by Professors Berkey and Paige was submitted to the Authority. The conclusions of this report are as follows:

It was concluded by Professors Berkey and Paige, Geological Consultants to the Authority, that the Mackinac Breccia and the elements composing it have the strength required to support the proposed bridge piers with an ample margin of safety. The collapse of ancient caverns and the primary brecciation occurred millions of years ago. The heavy loads of sediment that subsequently were deposited over the breccia have effected a consolidation of the rocks, and ample time has elapsed for recementation. They further concluded that the shales that are present will not "flow" toward the valley walls under the moderate stresses induced by the load of the bridge.

In addition, the Authority requested Mr. W. W. McLaughlin, Director of Testing and Research of the State Highway Department, and Professor W. S. Housel of the University of Michigan to make compression tests on samples of the material and also to make "in-place" loading tests. The conclusions of this report by Professor Housel dated March 1951 are as follows:

"In conclusion it may be pointed out that the most positive data from the loading tests indicate a yield value of approximately 60 tons per sq. ft. or about four times the suggested design capacity for dead load and normal live load. Furthermore, it should be emphasized that the loading tests were made on shale selected as the most unfavorable of the rocks in the foundation and at a selected location where the shale itself appeared to be the weakest found in the area. Subsequently, the tests were made under the most unfavorable conditions and then further reduced by extrapolation of size effect under the least favorable assumption that could be deduced from the test data. Under this combination of circumstances the final answer from the loading tests is still a demonstration that insofar as bearing capacity of the foundation is concerned there can be little question of the practicability of the construction of a major bridge at the Straits of Mackinac."

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3. Geology of the Mackinac Straits Region - Kenneth K. Landes, George M. Ehlers and George M. Stanley. Biennial Report of the Geological Survey Division, State of Michigan, 1944.

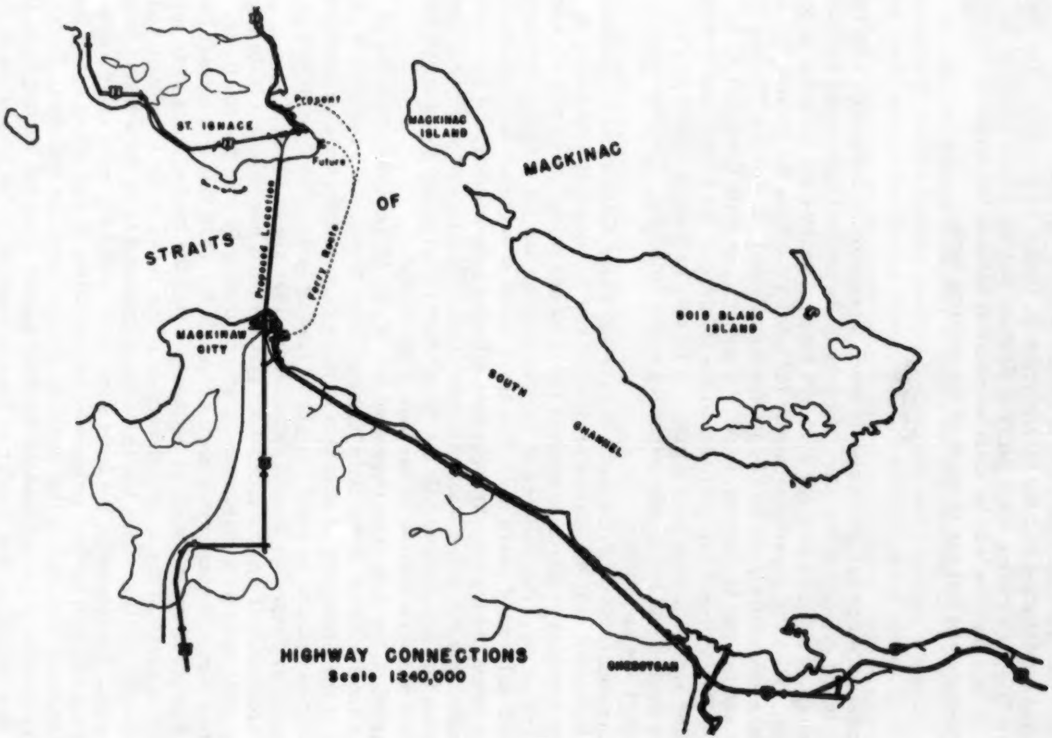


Fig. 4. Location Map of Bridge and Connecting Highways.

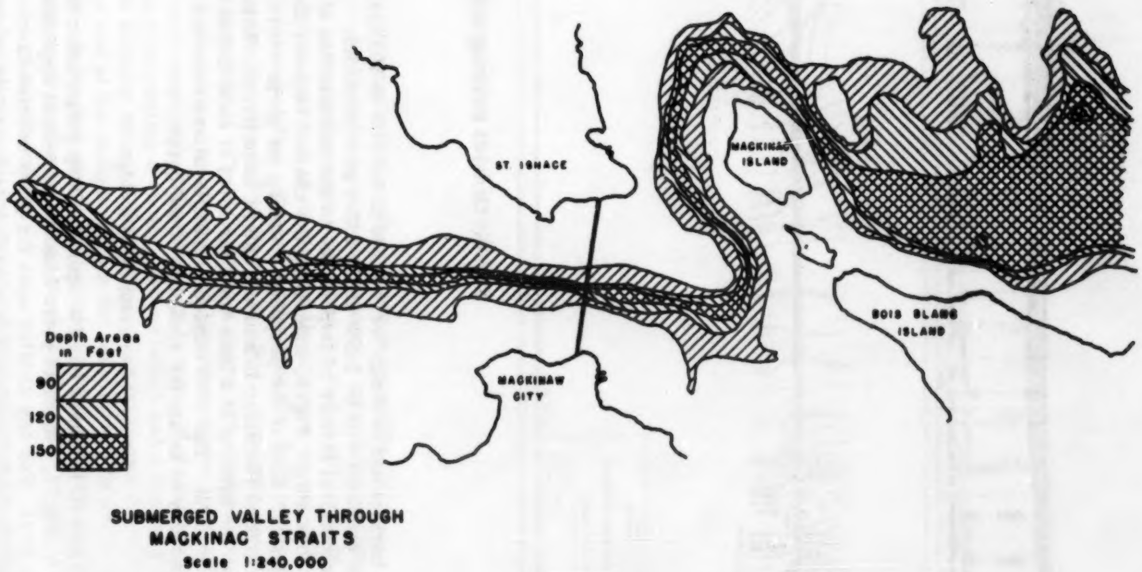


Fig. 5. Submerged Rock Gorge in Channel of Mackinac Straits.

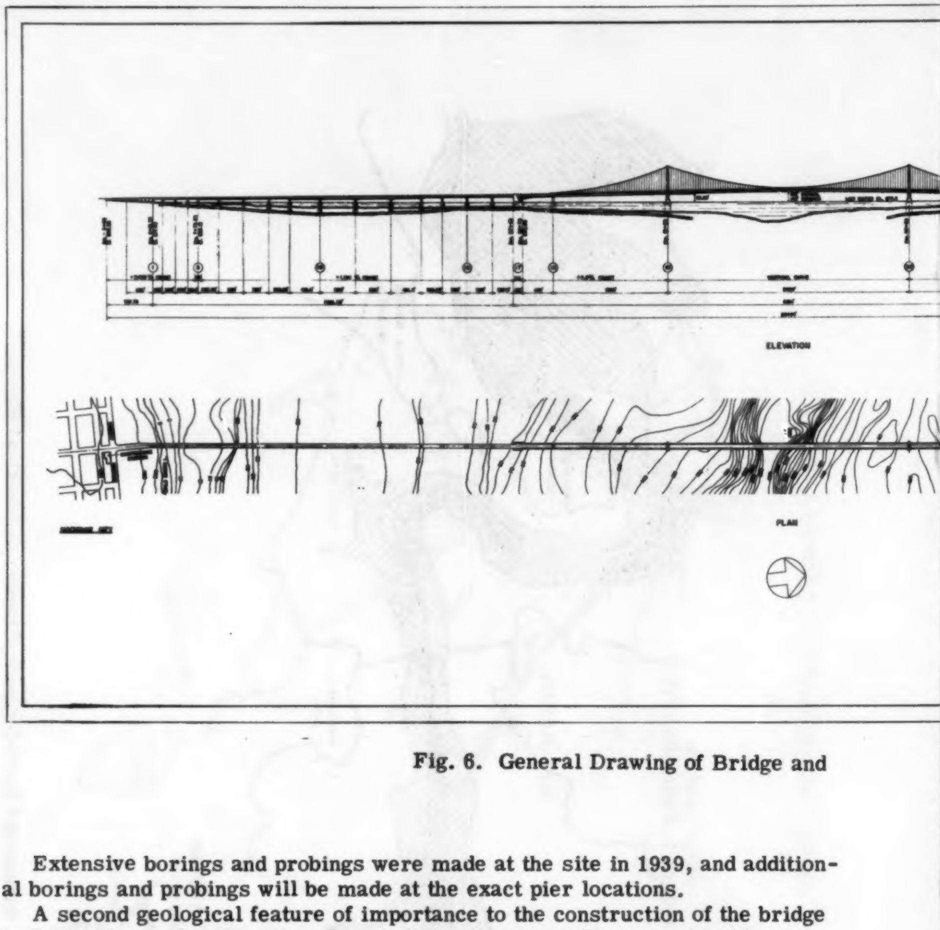


Fig. 6. General Drawing of Bridge and

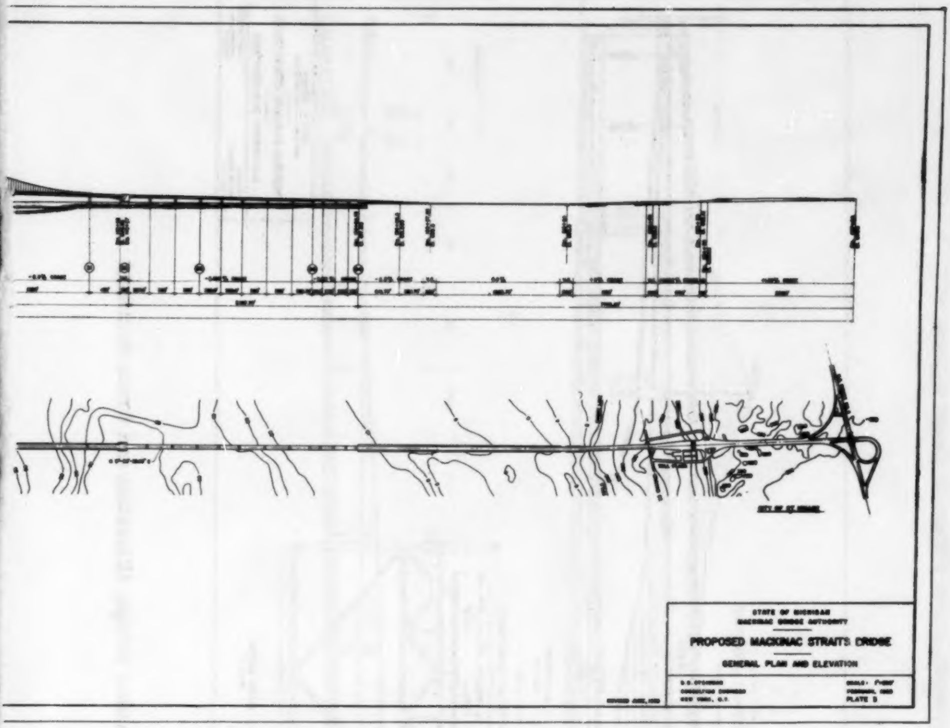
Extensive borings and probings were made at the site in 1939, and additional borings and probings will be made at the exact pier locations.

A second geological feature of importance to the construction of the bridge is the hidden rock gorge, Fig. 5, underlying the channel between Mackinaw City and St. Ignace. East of the proposed crossing the gorge veers north, makes a loop around Mackinac Island and enters Lake Huron. This gorge was eroded through the breccia at a time when the level of Lake Huron was much lower than at present. The 1939 subaqueous explorations extended to depths that were necessary to locate the rock-bed of the gorge.

General Description of Bridge

A span of 3,800 ft. has been fixed to span the deep gorge under the main channel, Fig. 6, Fig. 7, with main piers founded on rock at approximately 195 ft. below lake level. For any shorter span the piers become excessively deep and expensive. The only feasible type of structure for a span of such length is a suspension bridge.

For economy, side spans of 1,800 ft. with unloaded backstays of 470 ft. are used. This permits the anchorages for the cables to be placed where suitable rock foundations are found at the moderate depths of 86 ft. and 70 ft. below



Approach Spans. (Plan and Elevation.)

lake level for the south and north anchorage respectively.

A number of alternate layouts made for the remainder of the crossing over the waterway between the south shore and the end of the mole at the north shore have led to a series of continuous truss spans on concrete piers, Fig. 8, Fig. 9, as the best solution. Twenty spans over the deep portions of the waterway range in length from 560 ft. to 330 ft. Four spans near each shore have lengths of 160 to 200 ft. These lengths of spans are economically determined by the deep and massive piers required to withstand the ice pressures.

For the north approach, full advantage is taken of the existing mole or causeway by constructing a viaduct and a viaduct and a roadway on a fill placed on top of the existing mole. The maximum height of new fill will be 12 ft.

From the end of the mole and from the Mackinaw City shore the bridge roadway ascends by easy grades not exceeding 2.5 per cent to the towers of the main bridge. Over the center span of the main bridge the roadway is cambered on a parabolic curve.

These grades allow a minimum clear height above mean lake level of 135 ft. for a width of 3,000 ft. of the main channel. The minimum clear height at the center of the span is 148 ft.

The four-land roadway is 48 ft. wide between curbs and includes a 2-ft. wide, low center mall. The walkways are 3 ft. wide between curb and railing.

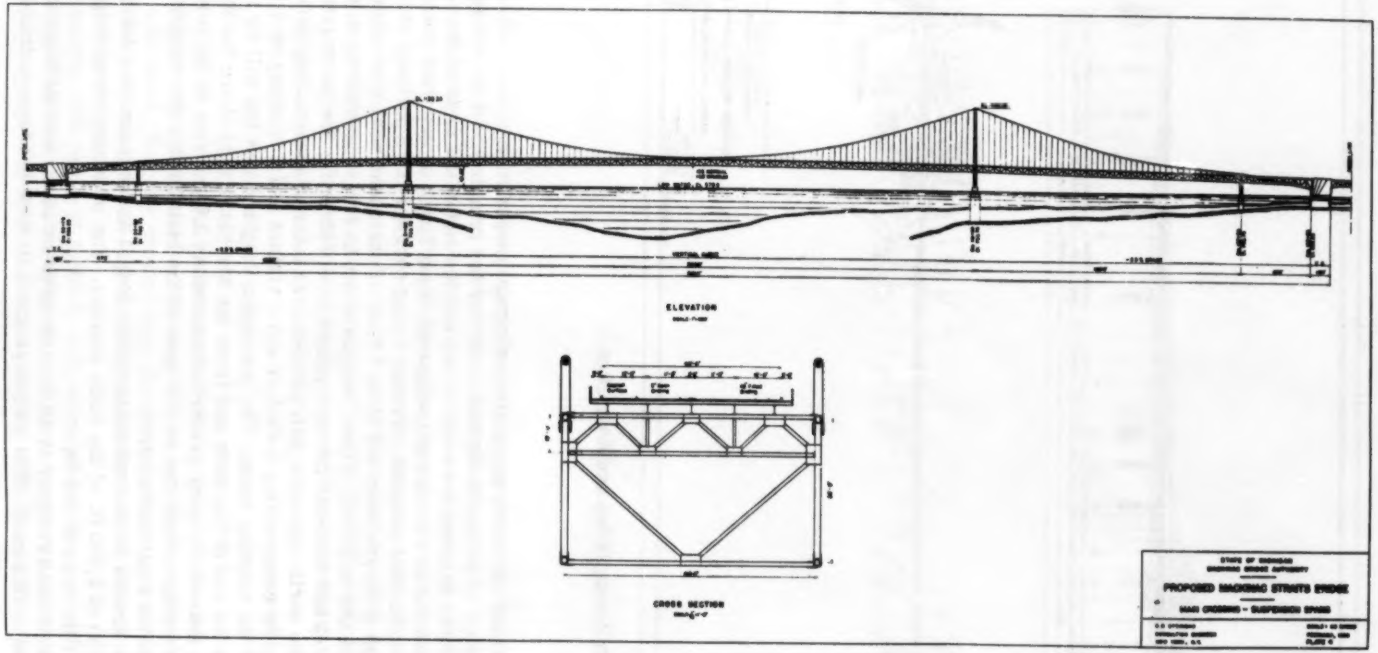


Fig. 7. General Drawing of Suspension Bridge. (Elevation and Cross Section.)

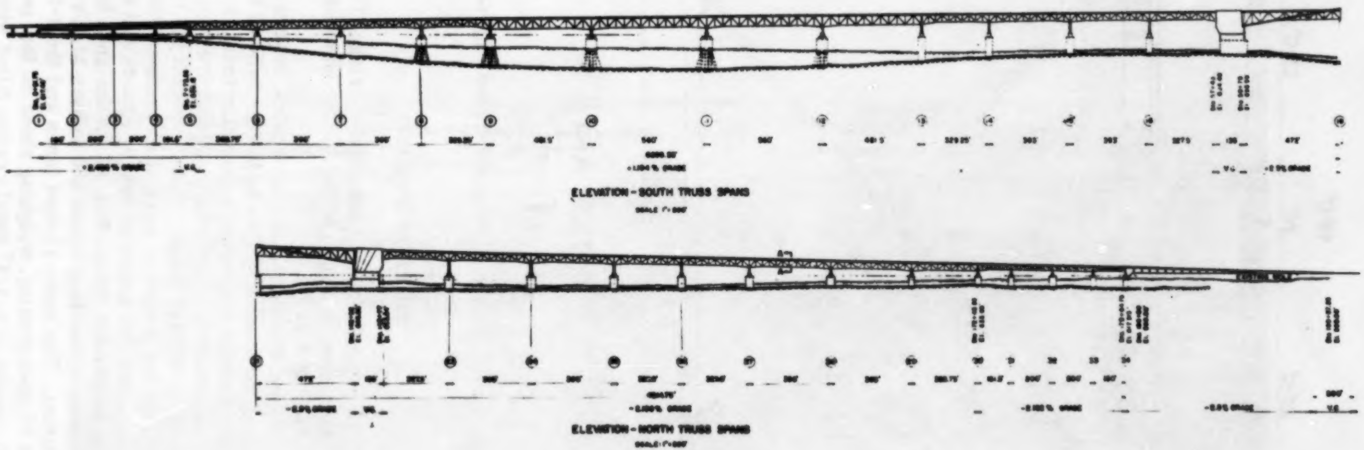


Fig. 8. General Drawing of Continuous-Truss Approach Spans. (Elevation.)

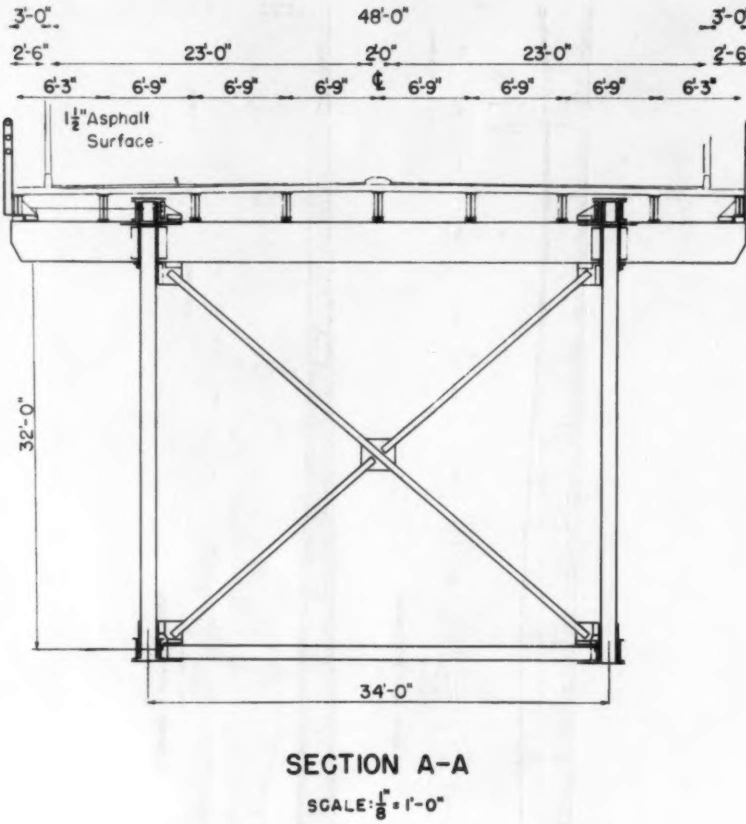


Fig. 9. Cross-Section of Continuous-Truss Approach Spans.

Suspended Structure

With a central span of 3,800 ft. the suspension bridge, Fig. 10, across the main channel will be second in length to the Golden Gate Bridge in San Francisco which has a span of 4,200 ft.

In its major carrying members, i.e., the cables, towers and anchorages, Fig. 11, the design of the Mackinac Straits Bridge follows closely the practice established by other modern long-span suspension bridges.

The suspended structure includes two stiffening trusses, 68 feet center to center, one in the plane of each cable. They transmit the floor loads to the suspenders and stiffen the structure against distortions due to live load and against oscillations under the action of dynamic loads and wind forces.

The floor of the suspended spans, Fig. 12, is designed to be light in weight for maximum economy in the long spans and to have highly favorable aerodynamic characteristics. The inner 11-foot lanes and the 2-foot center mall will be constructed of 5" open grating, weighing about 20 lbs. per sq. ft. The outer 12-foot lanes will consist of 4-1/4" steel grating filled with lightweight

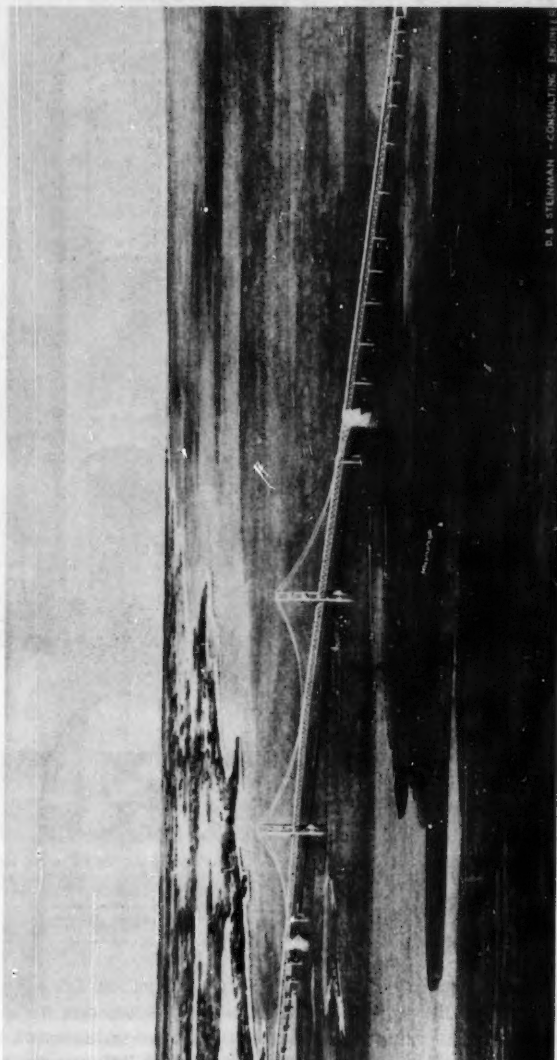


Fig. 10. Perspective Drawing of Suspension Bridge. (3800-ft. Span.)

Fig. 11. Perspective Drawing of Suspension Bridge. (Tower View.)

concrete and topped by a bituminous wearing surface, to weigh a total of 65 lbs. per sq. ft. The major part of the traffic will use the outer solid lanes, while the inner open grating lanes will be used mainly during peak-load hours. The emergency walkways will also be constructed of open grating. The grating for the roadways, and walkways, as well, will be supported on 12" cross-beams

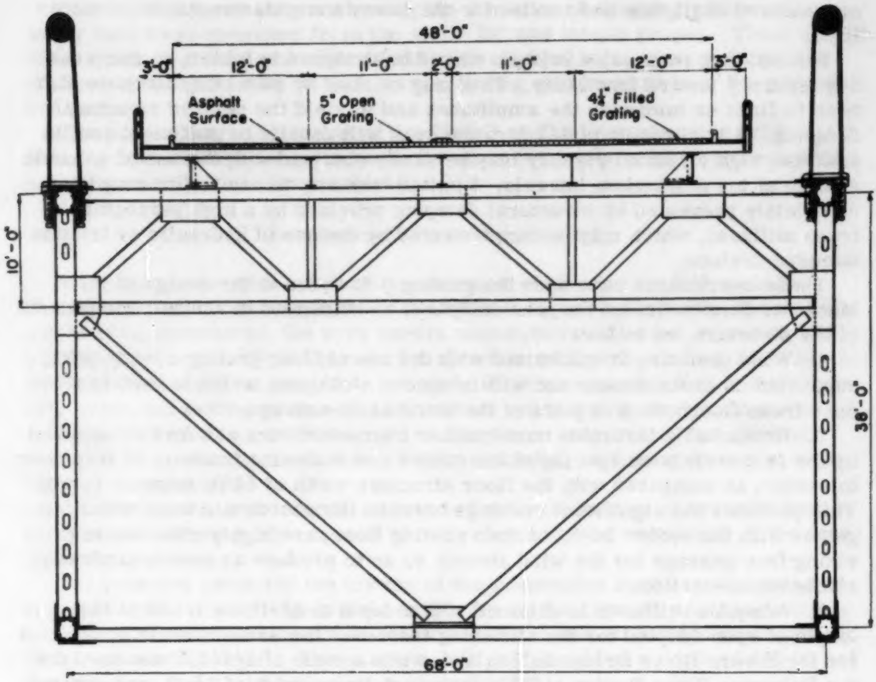


Fig. 12. Cross-Section of Suspension Spans. (Design for Aerodynamic Stability.)

which in turn will rest on five rows of longitudinal stringers, continuous over two 39-ft. panel lengths.

Aerodynamics

Following the failure of the original Tacoma Narrows Bridge in 1940, extensive research and theoretical analysis have been devoted to the matter of the action of suspension bridges under aerodynamic forces. This work has been actively prosecuted both in this country and in Europe. The basic conclusions resulting from these investigations can be summarized by stating:

First, that suspension bridges should be designed to present a form which will permit the greatest possible circulation of the wind stream through and across the structure. Thus the vertical force or lift, the horizontal force or drag, and the moment or torsion tending to twist the structure are minimized. In addition, the tendency to instability resulting in the cumulative building up of oscillations or negative damping for which the induced resultant vertical force for each cycle is in the direction of the motion of the span, is minimized

or rendered negligible and confined to the lower non-catastrophic wind velocities.

Second, that suspension bridges should be designed to inhibit or damp out any tendency toward instability. This may be done by providing adequate stiffness to limit or minimize the amplitudes and to yield the desired structural damping. A truss depth of 1/100 of the span will usually be sufficient and, in addition, high torsional rigidity may be easily obtained with the use of a double system of top and bottom laterals. Limited tendency to oscillation may be completely prevented by structural damping provided by a high percentage of truss stiffness, which may be supplemented by the use of hydraulic or friction damping devices.

These conclusions have been the guiding principles in the design of the Mackinac Straits Bridge Suspension Spans, as evidenced in various components of the structure, as follows:

1. Wind pressure is minimized with the use of floor grating open in part, supported on cross-beams and widely spaced stringers, which in turn rest on open truss floorbeams in place of the usual solid-web construction.

2. Remarkably favorable aerodynamic characteristics are further assured by the relatively wide spacing of the cables and stiffening trusses, 68 ft. center to center, as compared with the floor structure width of 48 ft. between curbs. This provides the significant openings between the chords and floor which, together with the center 24-ft. of open grating floor, are highly effective in providing free passage for the wind stream so as to produce an aerodynamically stable cross-section.

3. Adequate stiffness is obtained with a depth of 38-ft. or 1/100 of the length of span adopted for the stiffening trusses. The same ratio is being used for the Severn River Bridge in England, while a ratio of 1/107.5 was used for the Delaware River Bridge at Wilmington. A truss depth of 25-ft. corresponding to a ratio of 1/168, was used for the 4,200-ft. span Golden Gate Bridge; the depth-ratio adopted for the Mackinac Bridge is 68 per cent greater.

4. Torsional rigidity is very substantially increased with the use of a double system of lateral trusses, one in the plane of the top chords and one in the plane of the bottom chords, combined with stiff sway frames located at alternate panel points throughout the structure. The double lateral system increases the torsional stiffness many fold.

Under the direction of the engineers, several series of wind-tunnel tests have been made on a section model of the suspended structure by Prof. F. J. Maher at Virginia Polytechnic Institute. For the wind-tunnel tests, a scale-model was constructed by Prof. Maher to represent a 120-foot length of bridge.

Graphs giving the variation of aerodynamic lift, drag and moment with angle of attack of the wind for this section model under static tests have been plotted after the usual minor adjustments for slight asymmetry of wind tunnel mounting. The slope of the lift graph for horizontal wind and for positive angles of attack or upward inclined wind is almost horizontal, indicating very favorable aerodynamic characteristics. When the lift graph is corrected for drag, the slope is increased to a maximum of +1.3 as compared to the much higher slope +7.3 of the lift graph for the Golden Gate Bridge.

At a wind velocity of 100 M.P.H. and for zero angle of attack the wind force or drag for the Mackinac Bridge, according to the wind-tunnel tests, is 670 lbs. per foot of bridge, and the upward vertical lift is 50 lbs. per foot of bridge. The bridge is designed with approved factor of safety for horizontal wind load of 50 lbs. per sq. ft. equal to 960 lbs. per foot of bridge, or 44 per cent higher, corresponding to a wind velocity of 120 M.P.H.

Stability response graphs showing the variation of damping with wind velocity have been computed from the static lift and torque graphs. These curves show a high degree of positive stability for all wind velocities, and they are confirmed by the results of tests on oscillating section models of the proposed bridge.

The proposed cross-section of the Mackinac Straits suspension bridge is found by both theory and tests, to be the most favorable bridge cross-section, aerodynamically, thus far developed.

Suspension Bridge Foundations

After careful consideration of the data concerning ice conditions in the Straits and further investigation of the latest information of ice pressure on engineering structures, the very severe assumptions of an ice pressure of 115,000 pounds and (65,000 pounds for circular surfaces) per lineal foot of pier width at the water line have been adopted. This assumed loading is considerably greater than that generally assumed for engineering structures under comparable climatic conditions, and is five times as great as the maximum pressure theoretically attainable or ever recorded, according to recent engineering literature.[4]

Foundation construction will be carried out with the use of open-dredged caissons for the major piers, and of cofferdams for the remainder of the foundations.

The concrete piers for the towers of the suspension span are composed of two cylindrical concrete pedestals supported on the circular caisson concrete base at an elevation of eight feet below lake level and extending to a height of 25 feet above lake level. The caissons will be founded at a depth of 195 ft. below lake level, and will have a diameter of 116 ft.

All piers will be armored with wrought iron plates at lake level for protection against wave and ice action, and the shafts will be shaped to break the ice and minimize the ice pressure.

The cable anchorages are massive concrete structures which resist the pull of the cables and transmit this reaction to the underlying rock. The total pull of the two cables at each anchorage is approximately 30,000 tons; and the total yardage of concrete in each anchorage averages approximately 85,000 cu. yds. Through proper distribution of the mass of concrete, with hollow chambers in the upper section, the resultant of the cable pull and anchorage weight is so located as to minimize the loads on the base of the foundation. The anchorage foundations extend to depths of 86 ft. and 70 ft. below water, and will therefore be constructed in open cofferdams.

The pier for the south cable bent at the end of the side span will extend to a depth of 128 ft. below water and will be built as an open caisson.

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4. "Thrust Exerted by Expanding Ice Sheet", by Edwin Rose, 1947 Transactions ASCE Pg. 871.
"Ice Pressure Against Dams: Studies of Effects of Temperature Variations", by Bertil Lofquist, Separate No. 160, ASCE.
"Ice Pressure Against Dams: Some Investigations in Canada", by A. D. Hogg, Separate No. 161, ASCE.
"Ice Pressure Against Dams: Experimental Investigations by the Bureau of Reclamation", by G. E. Monfore, Separate No. 162, ASCE.
"Pile Foundations", by R. D. Chellis, McGraw-Hill Book Co., Pg. 173.

Conclusion

The climatic conditions, and especially the ice, limit the working season for the construction of the piers of the main crossing to the eight months of April to November inclusive.

Four construction seasons will be required to complete the project. Construction cost is estimated at $79,274,250 including contracts with the American Bridge Division of the U. S. Steel Corporation for the Steel Superstructure and with Merritt-Chapman and Scott Corporation for the substructure.

The total amount of a bond issue to include all costs of constructing and financing the Mackinac Straits Bridge is $99,800,000. The estimated revenues will provide a minimum coverage of 1.47 in 1959, and an average annual coverage of 1.94 over a period of 35 years to 1993. However, it is estimated that all bonds will be retired in a period of 18 years, by 1976, in accordance with the traffic revenues estimated by Coverdale & Colpitts.

Feasibility of the Mackinac Straits Bridge has been amply demonstrated both engineering-wise and financially. Its necessity to the economic development of the Michigan Upper Peninsula is unquestioned, and the benefits that will flow to the State of Michigan and the Great Lakes Area by the building of the Mackinac Straits Bridge are recognized. It is the hope of all who are connected with the project, that it will be financed before the end of this year.

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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DECEMBER: 359(AT), 360(SM), 361(HY), 362(HY), 363(SM), 364(HY), 365(HY), 366(HY), 367(SU)[c], 368(WW)[c], 369(IR), 370(AT)[c], 371(SM)[c], 372(CO)[c], 373(ST)[c], 374(EM)[c], 375(EM), 376(EM), 377(SA)[c], 378(PO)[c].

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c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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